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Research Article

Investigation on Domain Pinning Mechanism in Nanometer Hard Magnetic Materials

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The domain pinning mechanism was investigated in nanometer hard magnetic materials. The pinning fields of domain wall at different inhomogeneities were studied respectively. And exchange-coupling coefficient α_{ex} was investigated too. The results showed that α_{ex} is proportional to the ratio of inhomogeneity thickness $\mathrm{r_o}$ to wall width δ_{m} for narrow inhomogeneity, while it decreases with enhancement of $\mathrm{r_o}/\delta_{\mathrm{m}}$ for extended inhomogeneity. At a certain value of $\mathrm{r_o}$, exchange-coupling coefficient and pinning fields will reach the maximum. Exchange-coupling interaction and pinning fields are greatly influenced by inhomogeneity. Control range of inhomogeneity may obtain higher coercivity.

1. Introduction

In recent years, nanocomposite magnets have attracted much attention due to high theoretical energy product, which was recorded as high as 1 $\mathrm{MJ/m^3}$ [1]. However, an equally important uncertainty is coercivity mechanism in nanometer magnetic materials. Therefore, attention has been focused on coercivity mechanism [2–5]. Currently, there are mainly two coercivity mechanisms, nucleation and pinning. Kronmüller et al. [5] proposed that the coercivity of nanocomposite magnets was controlled by nucleation process of reverse domains and introduced a microstructural parameter α_{ex} to describe the effect of exchange-coupling interaction on coercivity, leading to $\mu_0 H_c = \alpha_k \alpha_{ex} \mu_0 H_N^{\min} - N_{eff} J_s$ (coercivity experiential formula). Zhang et al. [6] suggested both nucleation and domain–wall pinning model can be expressed as coercivity experiential formula. Experimentally, elemental additions were found to form precipitates at grain boundary [7, 8]. The properties of grain boundary are different from main phase. Therefore, there is inhomogeneous area in nanometer magnetic materials, which plays an important role in pinning domain wall. In this paper, pinning fields of domain wall H_c were calculated by considering inhomogeneous area. And corresponding exchange-coupling coefficient α_{ex} was investigated too.

2. Calculation Model

2.1. Inhomogeneous Area. Experimentally, elemental additions were found to form precipitates at grain boundary [7, 8]. Properties of grain boundary are different from the main phase. Additionally, due to the exchange-coupling interaction between grains, properties of grain edge have changed too. It is assumed that grain boundary and area influenced by exchange-coupling interaction form inhomogeneous area. Referring to K_1_profile given by Kronmüller [9], we assume anisotropy at inhomogeneous area is as follows:

$$K_1(r) = K_1 - \frac{nK_1}{ch^2(r/r_o)}, \tag{1}$$

where $\mathrm{r_o}$ is inhomogeneity thickness. K_1 is first anisotropy constant. n is a number no larger than 1, which denotes reduction K_1 in inhomogeneous area. The variation of anisotropy at inhomogeneous area is shown in Figure 1.

2.2. Coercivity Theory. Inhomogeneous area is regarded as strong planar pinning centers. When inhomogeneity thickness $\mathrm{r_o}$ is smaller than wall width δ_m, coercive field is given [10]:

$$H_c = \frac{1}{3\sqrt{3}} \frac{2K_1}{M_s} \frac{\pi d}{\delta_m} \sum_1^n \left(\frac{A}{A^{i,i+1}} - \frac{K_1^i}{K_1} \right) - N_{eff} M_s, \tag{2}$$

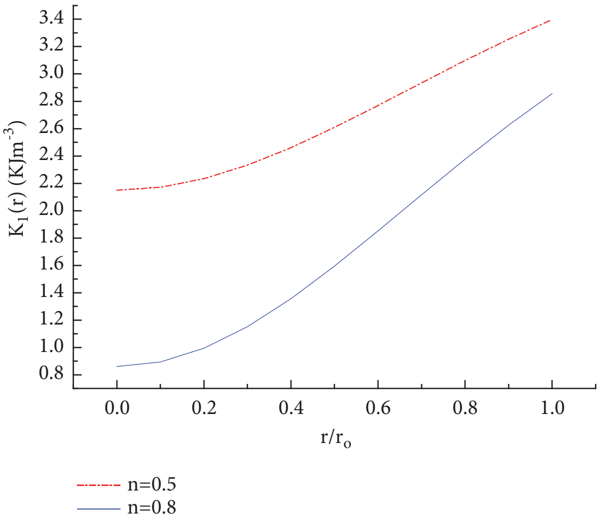

Figure 1: Variations of anisotropy K_1(r) in inhomogeneous area.

where $A^{i,i+1}$ corresponds to the local exchange constant between adjacent layers i and i+1. Similarly, K_1^i corresponds to the local anisotropy constant of the ith layer. δ_m is the wall width. The term $N_{\text{eff}}M_s$ takes care of demagnetization fields resulting from grain surfaces and volume charges. It is assumed that the n perturbed planes have equivalent properties (A' and K_1' are equal). And we assume A' of perturbed planes is equal to A. Coercivity is written as

$$H_c = \frac{1}{3\sqrt{3}}\frac{2K_1}{M_s}\frac{\pi r_o}{\delta m}\left(1-\frac{K_1'}{K_1}\right) - N_{eff}M_s, \tag{3}$$

where $r_o = md$ denoting inhomogeneous area thickness.

When r_o is larger than δ_m, the coercive field is determined by

$$H_{c_c}^{ij} = \frac{1}{2M_s}\left(\frac{d\gamma}{dr}\right)_{\max} - N_{eff}M_s, \tag{4}$$

where $(d\gamma/dr)_{\max}$ denotes maximum slope of the wall energy given by $\gamma = 4\sqrt{A_1K_1(r)}$. K$_1$(r) is anisotropy at inhomogeneous area.

2.3. Coefficient for Exchange-Coupling Interaction. Compared with coercivity experiential formula, expressions of exchange-coupling coefficient α_{ex} are given. For thin inhomogeneity ($r_o < \delta_m$), exchange-coupling coefficient α_{ex} is written as

$$\alpha_{ex} = \frac{1}{3\sqrt{3}}\frac{\pi r_o}{\delta_B}\left(1-\frac{K_1'}{K_1}\right). \tag{5}$$

In this case, for $K_1' = K_1(r_o/2)$ and n=0.8, $\alpha_{ex} = (7\sqrt{3}/100)(\pi r_o/\delta_B)$ is obtained.

For thick inhomogeneity ($r_o > \delta_m$), α_{ex} is written as

$$\alpha_{ex} = \frac{n\delta_m}{\pi r_o}\left(\frac{d\sqrt{K_1(r)}}{dr}\right)_{\max}. \tag{6}$$

And when n equals 0.8, $\alpha_{ex} = 12\delta_m/25\pi r_0$.

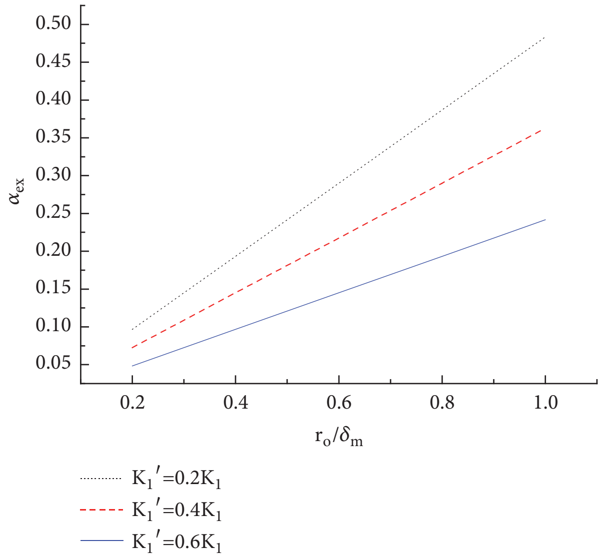

Figure 2: Variations of exchange-coupling coefficient α_{ex} with the ratio of r_o to δ_m for narrow inhomogeneity.

3. Results and Discussion

We calculated coercivity and corresponding α_{ex} by using intrinsic magnetic parameters of $Nd_2Fe_{14}B$ (K_1=4.3MJ/m^3[5], J=1.6T, M_s=1280KA/m[11]).

Figure 1 shows variations of anisotropy K_1(r) in inhomogeneous area. It can be seen that K_1(r) increases with enhancement of ratio of r to r_o. The value of anisotropy of area close to grain core is larger, because it is influenced to a fewer degree by exchange-coupling interaction. It is also shown in Figure 1 that K_1(r) decreases with increasing n. n denotes the decrease K_1 in inhomogeneous area. Exchange-coupling interaction and inhomogeneity decrease anisotropy.

Figure 2 shows variations of exchange-coupling coefficient α_{ex} with ratio of r_o to δ_m for narrow inhomogeneity. It can be seen that α_{ex} is proportional to r_o/δ_m in this case. For smaller r_o, exchange-coupling interaction is strong, and the effects of exchange-coupling interaction on anisotropy and coercivity are dominant. The enhancement of α_{ex} mainly results from influence of exchange-coupling interaction. Figure 3 shows variations of exchange-coupling coefficient α_{ex} with ratio of r_o to δ_m for extended inhomogeneity. It can be seen that α_{ex} decreases with increasing of r_o/δ_m for certain value of n. For extended inhomogeneity, the effect of defect on anisotropy and coercivity is dominant.

Figure 4 shows dependence of α_{ex} on ratio of r_o to δ_m. In transition region near 0.6, the broken curve indicates the transition between the approximations for narrow and extended inhomogeneities. As shown in Figure 5, the variation of coercivity and exchange-coupling coefficient is consistent. Inhomogeneity has great influence on coercivity. Magnetization reversal process is thought of as follows. Firstly, the antimagnetization core is formed in the nonuniform region. With enhancement of the antimagnetization field, domain wall displacement will encounter maximum resistance peak caused by exchange coupling interaction

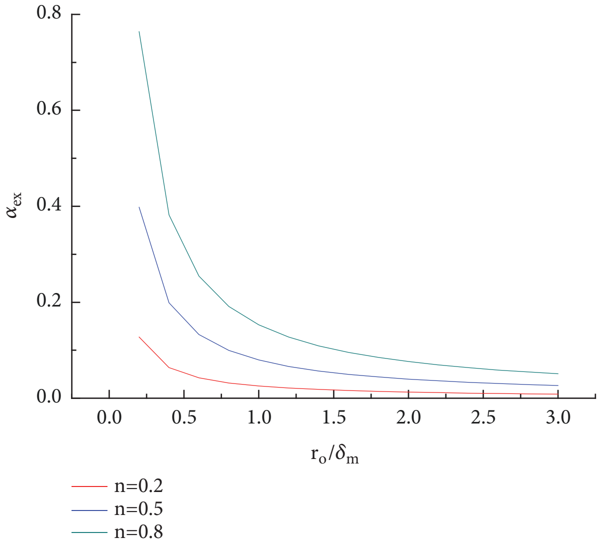

Figure 3: Variation of exchange-coupling coefficient α_{ex} with the ratio of r_o to δ_m for extended inhomogeneity.

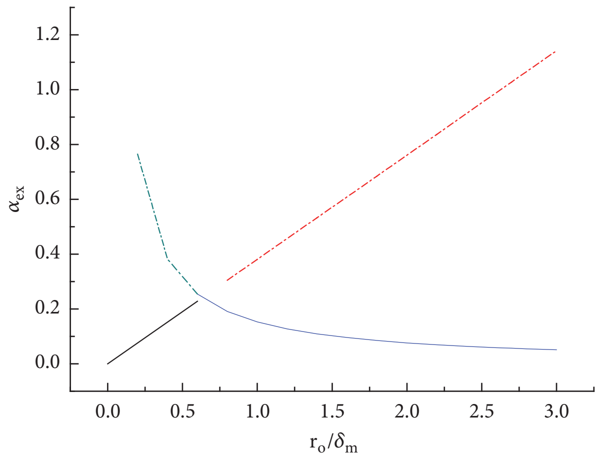

Figure 4: Dependence of α_{ex} on ratio of r_o to δ_m.

and inhomogeneity, and domain wall will have maximum irreversible displacement. Pinning field reaches the maximum value. With increasing inhomogeneity, area influenced by exchange-coupling interaction is larger for narrow inhomogeneity, while area influenced by exchange-coupling interaction is smaller with increasing range of inhomogeneity for extended inhomogeneity.

4. Conclusion

It is assumed that defect and grain edge influenced by exchange-coupling interaction form inhomogeneous area. Pinning fields and exchange-coupling coefficient α_{ex} corresponding to narrow and extended inhomogeneous area are investigated respectively. By considering different inhomogenities, pinning fields and exchange-coupling coefficent were studied. While the effect of defect on them is dominant for extended inhomogeneity. Coercivity depends greatly on microstructure.

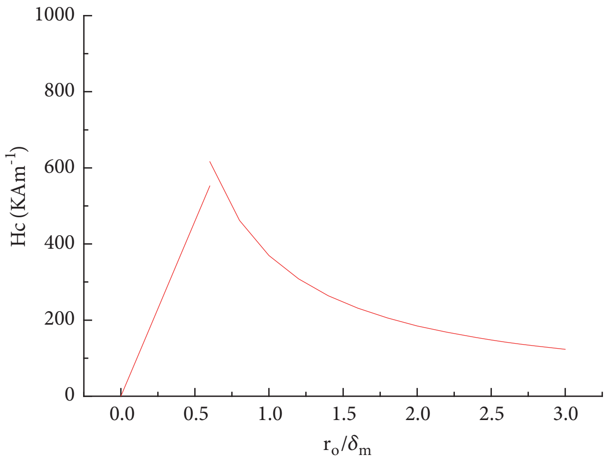

Figure 5: Dependence of coercivity on ratio of r_o to δ_m.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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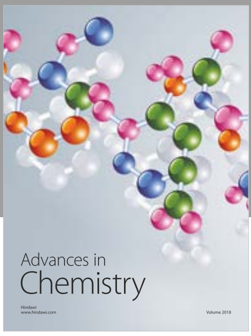
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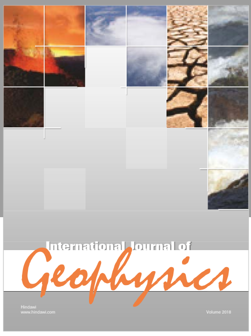
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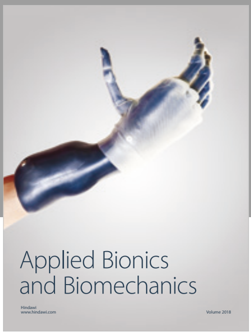
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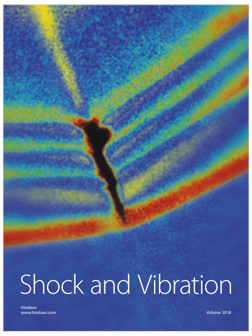
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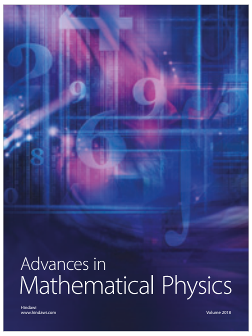
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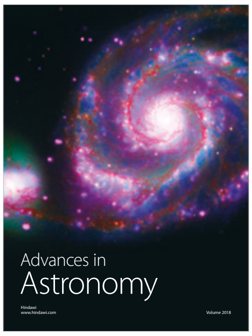
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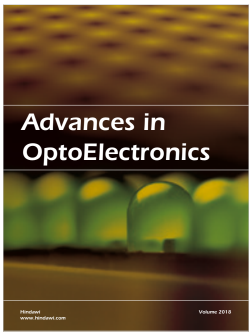
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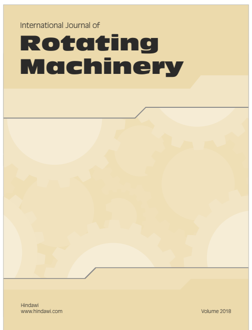
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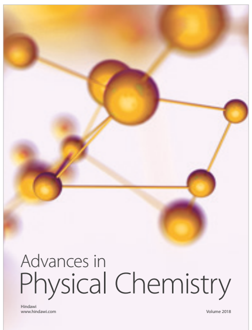
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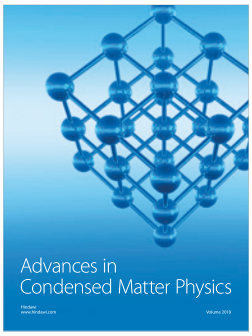
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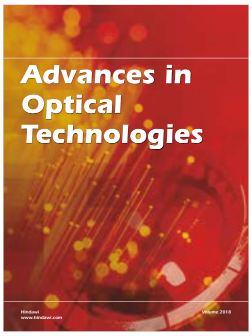
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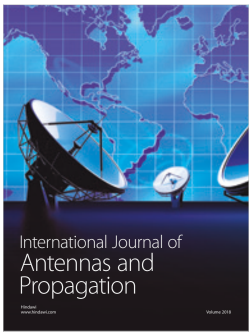
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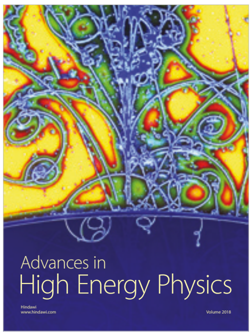
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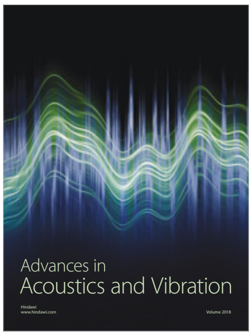
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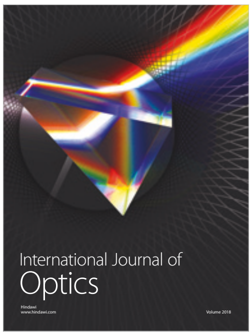
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